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Assessment of the Ecological Risks of Landslide Damages in the Carpathian Region

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Abstract

The dynamism of the landslides within the Carpathian region of Ukraine is because of the difficult engineering and geological conditions. High landslide den sity and significant population density contribute to the fact that environmental parameters worsen and require rational management. Permanent natural factors like clay flysch formation, fault tectonics, high seismic activity, and dense network of rivers mostly facilitate the active development of landslides in the Carpathian region. However, it is triggered by extreme long-term precipitation. The numerical parameters of population density, the landslide damage coefficient, and the predictive range of landslide intensification were selected to assess the ecological risk of damages in the area. The landslide dam age coefficient characterizes the tendency of the area to landslide development, considering all the factors contributing to the landslides. Risk, as a multifunctional calculated complex, includes the calculation of damage, according to which we can assess the possibility of risk for the human being while assuming the equal distribution of the population within the study area. The integral components of the risk are calculated based on the data gathered to assess the growth of risks in the future, considering the area distribution and predictive time series of the landslide intensification. This analysis has identified engineering and geological areas having the greatest risk to human life.

Keywords

Ecological risk; Integrated risk; Landslides; Assessment; Long-term prediction

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Introduction

The development of landslides within the Carpathian region has a significant impact on the state of natural and man-made safety and determines the search for new ways of forecasting to assess the risks of their negative effects. The spread and expansion of the landslides affect the environment with a cardinal change in the relief. Here, the extensive forest areas are being destroyed, the riverbeds are deforming. Besides, the consequences of the landslide intensification cause meaningful economic and social losses to the local population, roads and power lines. This occurs frequently in the fragile mountainous areas, where the greatest landslide damages can be observed.

Academic studies of the scholars pay special attention to the issues of the risks of landslide intensification and the needful early warning about the possible landslides in the mountainous areas. Bonnard, Forlati and Scavia (2004) present the method of risk management and mitigation strategy regarding the landslide consequences in the Alpine mountain valleys. Corominas *et. al*. (2014) recommended methodologies for quantitative analyses of the landslide hazard, damage and risks at different spatial scales. They suggested to adopt the managerial decisions for financial assessment of risks at the local and regional level. Abella and van Westen (2007) specified a procedure for creating quantitative landslide risk maps submitted to the national early warning system providing information about probable danger and the need of early evacuation of people from the landslide prone areas.

Overview of the Area and Study Trends

High water and floods may develop in the rivers in the Carpathian region several times a year. The map of engineering and geological areas of the study area is presented in figure 1. If the upper layer of soil contains the previous moisture, the floods will provoke the development of landslides. The State Emergency Service of Ukraine[1] classified the last high water on 17-29 June 2020, which covered the western regions. It is like a natural disaster at the state level. By the disasters, 349 populated localities and over 14,300homes were flooded; 3,500 household buildings, 654 kilometers of roads and 266 bridges were completely damaged in 2020. According to the preliminary estimates, more than UAH 1,000 million were required to repair the damaged facilities.[2] There was an intensification of the landslides.

The spread and intensity of developing exogenous geologic processes, landslides in particular, are influenced by the tectonic, seismic regime of the area, features of geological, geomorphological structure and hydrogeological conditions. Area zoning is necessary to determine the patterns of spread and development of exogenous geologic processes, landslides in particular. In Ukraine, the issue of environmental safety is dealt with at the state level. The Law 'On Basic Principles (Strategy) of the State Environmental Policy of Ukraine for the Period up to 2030'[3] (28.02.2019) was adopted in 2019. One of the tasks of the law is "to reduce the environmental risks by minimizing its effects on the ecosystems, social and economic development and the people's health. There is an introduction of ecological risk management based on a modelling in real-time with the involvement of the latest information technologies."

Relevant research papers of the different scholars, e.g., Rudko (1991), Rudko *et al.* (1999), Rudko and Erysh (2006), Adamenko, Rudko and Kovalchuk (2000), Ivanyuta and Kaczynski (2012), Kasiyanchuk (2015, 2016), Bodnar (2015), and Klymchuk *et al.* (2008), are devoted to the prediction and assessment of the natural disaster risk in order to understand dangerous geological processes.

[1] https://www.dsns.gov.ua/
[2] http://komekolog.rada.gov.ua/uploads/documents/35969.pdf
[3] https://zakon.rada.gov.ua/laws/show/2697-19#Text

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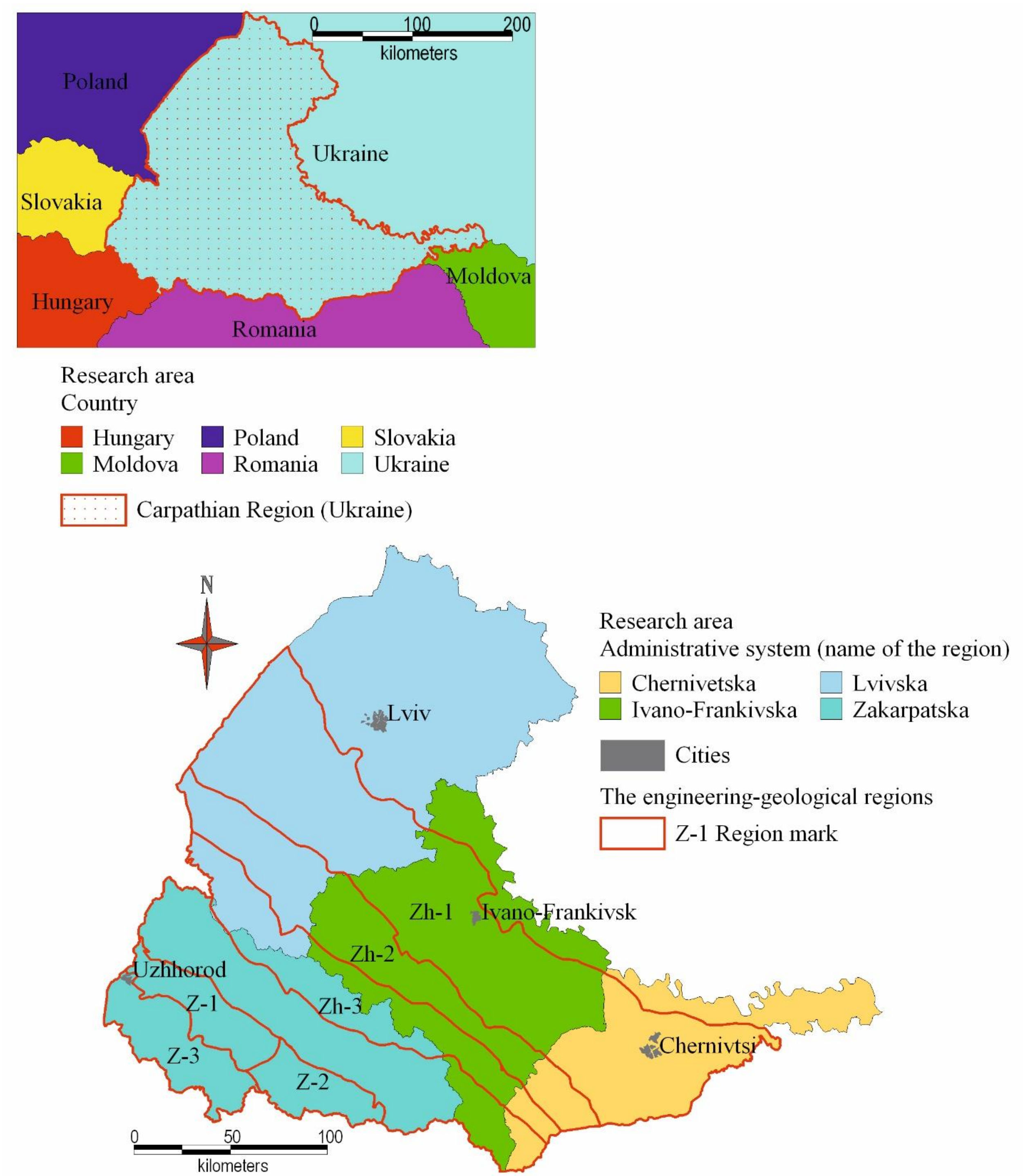

Figure 1: Engineering-geology maps of the study area

The spread and intensity of developing exogenous geologic processes, landslides, in particular, are influenced by the tectonic, seismic regime of the area, features of geological, geomorphological structure and hydrogeological conditions. Area zoning is necessary to determine the patterns of spread and development of exogenous geologic processes, landslides, in particular. According to the scheme of regional engineering geological zoning (Bodnar *et al.*, 2015), the studied area of Transcarpathian region and Chernivtsi region is located within the Transcarpathian Inner Depression and the Carpathian Fold System.

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This area, because of the differences in individual areas regarding the geological and climatic conditions of landslide development, was considered consisting of two separate regions: the Folded Carpathians and the Precarpathian Depression.

Methodology

This study was performed using the Geographic Information System MapInfo. An engineering geological zoning map with the contours of regions was drawn up. Since the studied region is characterized by zoning from northwest to southeast, main engineering and geological units are located in the same direction. The spatial database[4]included 2,339 landslides in Transcarpathian region and 1,119 landslides in Chernivtsi region (3,458 landslides in total) (figure 2). Such data set offers a possibility to conduct full analysis to assess risks based on an integrated time indicator. Nowadays, environmental risk modeling is performed through several approaches. The calculation of risk as an environmental and economic component of losses is basic tool. This article offers, for the first time, to expand and represent the principle, which would consider not only one component (population - the number of shifts) but also a full-fledged basis for developing a geo-information model based on spatial temporal analysis. This approach was implemented through the proposed method of calculating the environmental risk from the perspective of the negative effects of landslides.

Risk Assessment Technologies

The concept of 'environmental risk' defines the possibility of negative consequences that may arise because of landslides as they affect the health and safety for two reasons: first, a threat to human life during the landslide intensification; the second, huge economic losses with the destruction of the buildings, power lines, roads, which are located in the areas affected by the displaced rocks. Assessment of the environmental risk within the engineering and geological domain considers the registered landslides having special features of engineering and geological conditions of developing with the differences in the temporal factors, mode of landslide intensification(including the seismic activity), dynamic climatic factors such as annual temperature, annual precipitation, groundwater levels (Davybida *et al.*, 2018; Pona *et al.*, 2016; Tymkiv *et al.*, 2019) and solar activity (Shtohryn *et al.*, 2020), the influence of which is manifested indirectly through the air circulation, precipitation, and temperature. To determine the extent to which the engineering and geological regions, within the studied area, are covered by landslides, the 'damage coefficient' K_i, considering the influence of the natural factors and the tendency of the area developing the specified processes (Equation (1)), was used:

$$K_i = S_i / \sum S_i, \quad (1)$$

Where S_i is the area of landslides within the engineering and geological region; $\sum S_i$ is the area of engineering and geological regions.

Transcarpathian Inner Depression covers an area of 5.58 thousand square kilometers. The landslides develop in quaternary clay alluvial-diluvial deposits on the river slopes and in the weathered layer of volcanic rocks. By the type of displacement, they are landslides of flow and landslides of sideslip (Velychko *et al.*, 2019). 820 landslides were registered in total within an area of 74.7 square kilometers with the damage coefficient of 1.4%, and a population density of 96.63 people per square kilometer within the depression. Average values of the landslide characteristics are absolute marks of 416.5 meters and the longitudinal profile steepness is 20.8°. The landslides have small dimensions: the length is 335.8 meters; the width is 339.3

[4]https://geoinf.kiev.ua/publikatsiyi/shchorichnyky/

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meters; the average deposit thickness is 3.85 meters. The main factors contributing to the development of landslides include special features of the geological structure (Shtohryn *et al.*, 2021), fault tectonics, high seismic activity, and the river network's density of 0.8-1.6 kilometers per square kilometer, which often form the floods and develop the lateral erosion, humid climate and human activity (Davybida *et al.*, 2018). The landslide intensification for the studied period took place in 1970, 1974, 1980, 1998-1999, 2001, 2008, and in 2010.

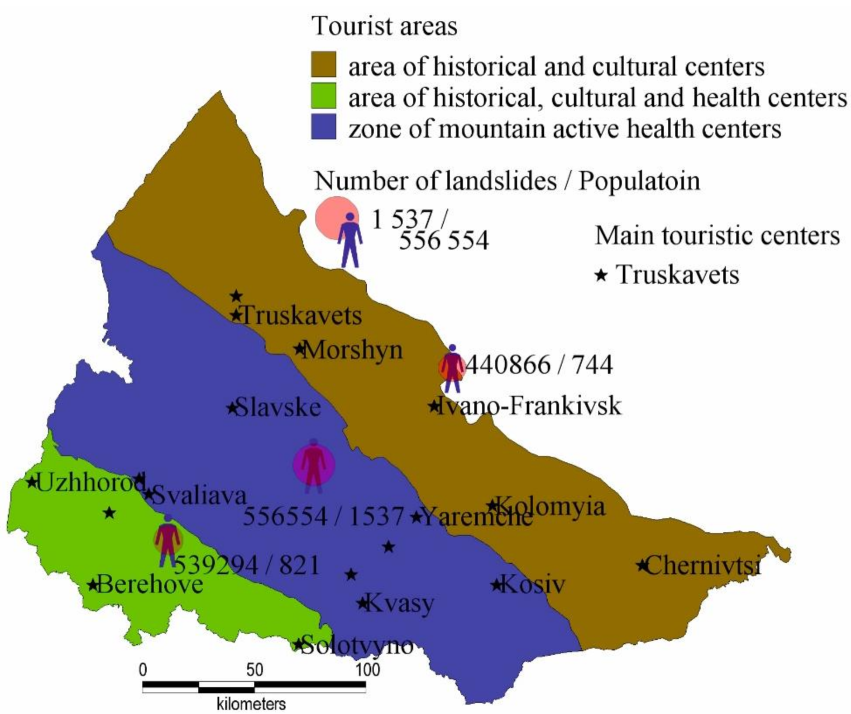

Figure 2: The map of the landslide activities, population and touristic zones

1,532 landslides were registered having an area of 256.17 square kilometers with the damage coefficient of 3% and the population density of 64.59 people per square kilometer in the studied Folded Carpathians expanded over an area of 8.62 square kilometer. Structural plastic flow landslides and complicated landslides, which develop at the junction of structural tectonic zones, were the most common. The flow landslides and landslides of sideslip predominate by the type of displacement. Important natural factors contributing to the development of the landslides include fine-grained clay flysch formation, which offers the conducive environment for landslides, seismic activity, a dense network of mountain rivers of 1.4-2.0 kilometers per square kilometer, significant relief energy, excessive atmospheric precipitation (average 1,180 mm per year), and human activity e.g., deforestation and slope cutting during construction works. The landslides are characterized by the following average parameters: absolute marks of 621.6 meters, the steepness of the longitudinal profile of 25.4°, the length of 442.2 meters, the width of 325.9 meters, and the deposit thickness of 13.1 meters. The landslide intensification for the studied period took place in 1970, 1974, 1980, 1998-1999, 2001, 2008 and in 2010.

The Precarpathian Depression within the studied region covers an area of 4.54 square kilometers, and it is the area that is the most damaged by the landslides. We have registered 744 landslides with an area of 351.6 square kilometers; the coefficient of damage is 7.8%, the population density is 97.2% people per square kilometer. Landslides of the Precarpathian Depression develop in quaternary clay alluvial-diluvial deposits, which accumulate in valleys of the Prut River and the Seret River. Absolute marks of the landslides are 270.7 meters, the steepness of the longitudinal profile is 17.2°, the length is 327.6 meters; the width is 1,046.5 meters, the deposit thickness is 4.9 meters. Besides the geological structure, the development of

landslides is affected by the density of the river network i.e.,1.11 kilometers per square kilometer, the frequent high water in the local rivers, the low groundwater level and human activity (cutting slopes during the construction of linear-type facilities, selection of gravel and crushed stones). Time series of the landslide intensification includes 1969-1970, 1974, 1979-1980, 1998, 2001, 2005, 2008, and 2010. As we can see from the above, for the engineering geological regions, there are both common periods of widespread landslide activity and different periods that are regional stages of landslides stipulated by the local regime of climatic parameters.

Assessment of Ecological Risk of Landslides

Risk is a complicated system of calculations that must primarily study the cause-and-effect linkage between the factors of spatial spread and temporal dynamics of landslides. An important step shall be the analysis of the area in terms of the spread of the landslide areas or likely impact on human life. The first component is calculated as the damage, which has the physical meaning of the process for the spatial spread of landslides. The second component is the probability of risk for a human being under the condition of even distribution of the population. The first component of the spatial spread of the risk of landslides for individual regions was calculated according to the formula (2):

$$R_{yp_i} = \sum_{i=1}^{n} f\left(\Phi_{ij}\right) \cdot K_i \text{ ...... (2)}$$

where $f(\Phi_{ij})$ is the value of the predicted probability of landslides within the region; K_i is the damage coefficient. The second component of the probability of risk formation for a human being within the individual engineering and geological regions was calculated according to the formula (3):

$$R_{pop_i} = \sum_{i=1}^{n} f\left(\Phi_{ij}\right) \cdot N / \sum S_i \text{ .... (3)}$$

Where $f(\Phi_{ij})$ is the value of the predicted probability of landslides within the region; N is the population within individual engineering and geological regions; $\sum S_i$ is the area of engineering and geological regions.

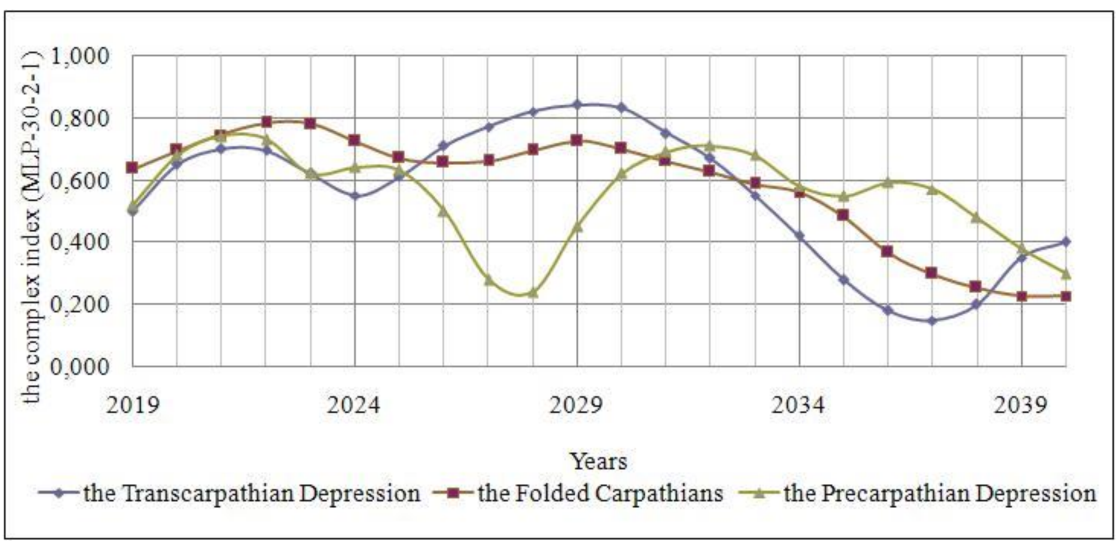

Figure 3: The temporal graphs of the probability of landslides

Figure 3 demonstrates the temporal graphs of the probability of landslides in an average of values based on three points and the prediction using the MathCad integrated mathematical package and neural networks (Shtohryn *et al*., 2020).

An integrated risk assessment is performed by accumulating risks, which allows to assess to which extent the potential danger is growing in the future, considering the spatial distribution and predictive time series of landslide intensifications. Figure 4 demonstrates the risks of damage in the areas (a scale on the left) and risks to the life of the population (a scale on the right).

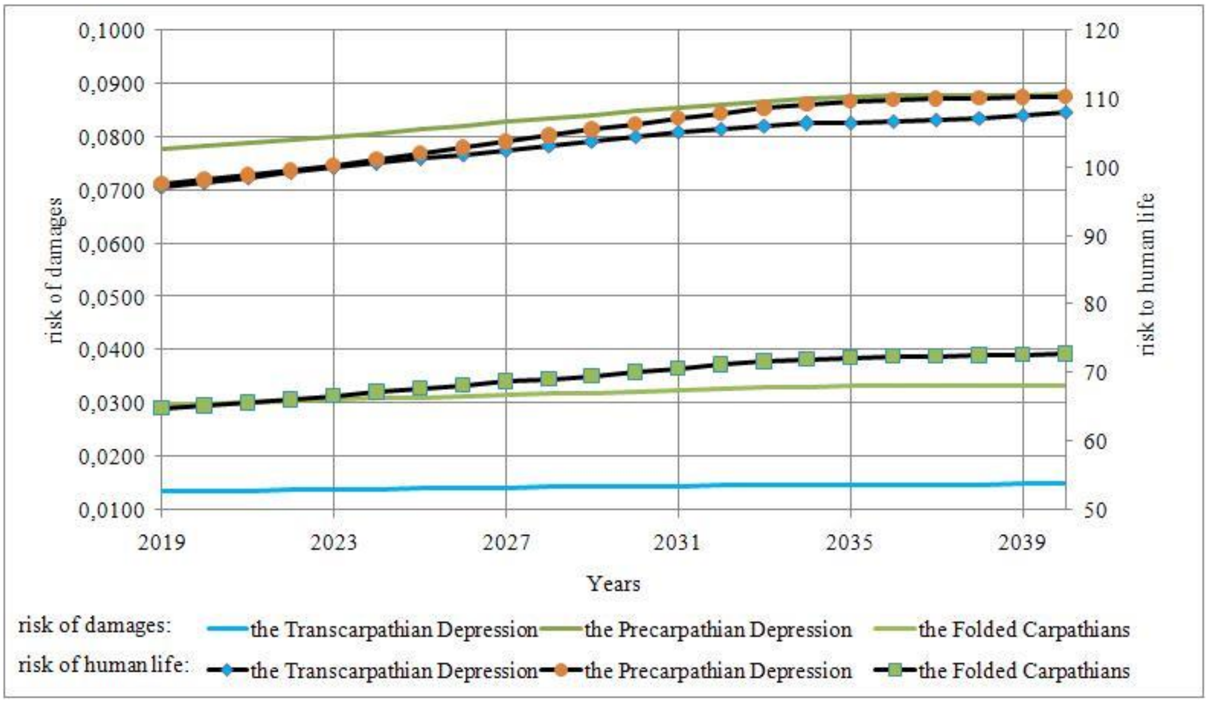

Figure 4: Natural environmental risk of long-term prediction of landslide possibility: the Transcarpathian Depression; the Folded Carpathians; the Precarpathian Depression

Analysis of the conducted calculations shows that the most dangerous region (in terms of growth of the areas covered by landslides) is the Precarpathian Depression, where the increase in the landslide damage is predicted by 12.32% for the twenty-year period forecast. For the Folded Carpathians, an increase in damage is predicted by 12.08%; for the Transcarpathian Depression region, the increase in the landslide damage is predicted by 11.72%.

Conclusion

The growth of the environmental risk from landslides closely relates to both the area of landslide development and the population density in the region. The calculated ecological and geological risks consider the peculiarities of temporal dynamics (the predicted possibility of landslide development), the spatial distribution of landslides (considering the differences in geological, tectonic, lithological structure, seismic, hydrological and climatic factors), and the population density within engineering and geological regions. Forecasting the possible intensification of the landslides and assessment of their spread should be considered while adopting the managerial decisions at the regional level in order to reduce the negative impact of landslides on the environment in terms of the economic and social consequences. Given the dynamics of landslide intensification and the growth of negative impact on the population while considering the time probability, the development of tourism infrastructure and its management need special planning

and scientific assessment. Engineering and geological conditions, combined with climate change, are crucial in the assessment of risks to human life and critical infrastructure in the Carpathian region. Intensive development of the tourism industry, poor planning and non-compliance with the requirements for construction in complex engineering geological conditions require the assessment of solutions based on a scientific approach that revolve around:

1. Understanding the risk as an ecological and economic basis for sustainable development of the region;
2. Creating a forecast time model of life risk, as a basis for building a system to prevent the negative consequences of the activation and development of landslides; and
3. Development of a geo-informational model of spatial forecast based on a time model of life risks at the local level as a basis for sustainable development in the future.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	No
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	No	Yes
Editing of the article/paper	Yes	Yes
Supervision	No	Yes
Project Administration	Yes	Yes
Funding Acquisition	Yes	Yes
Overall Contribution Proportion (%)	50	50

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Research involving Plants
During the research, the authors followed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora. Yes

Research on Indigenous Peoples and/or Traditional Knowledge
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(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)
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